



Offshore Code Comparison Collaboration within IEA Wind Task 23: Phase IV Results Regarding Floating Wind Turbine Modeling

Jonkman, J.; Larsen, Torben J.; Hansen, Anders Melchior; Nygaard, T.; Maus, K.; Karimirad, M.; Gao, Z.; Moan, T.; Fylling, I.; Nichols, J.

Total number of authors:
14

Published in:
EWEC 2010 Proceedings online

Publication date:
2010

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):

Jonkman, J., Larsen, T. J., Hansen, A. M., Nygaard, T., Maus, K., Karimirad, M., Gao, Z., Moan, T., Fylling, I., Nichols, J., Kohlmeier, M., Pascual Vergara, J., Merino, D., & Shi, W. (2010). Offshore Code Comparison Collaboration within IEA Wind Task 23: Phase IV Results Regarding Floating Wind Turbine Modeling. In *EWEC 2010 Proceedings online* European Wind Energy Association (EWEA).

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Offshore Code Comparison Collaboration within IEA Wind Task 23: Phase IV Results Regarding Floating Wind Turbine Modeling

J. Jonkman

*National Renewable Energy Laboratory
(NREL), United States of America
jason.jonkman@nrel.gov*

T. Larsen and A. Hansen

*Risø National Laboratory, Technical
University of Denmark (Risø-DTU), Denmark*

T. Nygaard and K. Maus

*Norwegian University of Life Sciences (UMB),
Norway*

M. Karimirad, Z. Gao, and T. Moan

*Norwegian University of Science and
Technology (NTNU), Norway*

I. Fylling

MARINTEK, Norway

J. Nichols

*Garrad Hassan & Partners Limited (GH),
United Kingdom*

M. Kohlmeier

*ForWind, Leibniz University of Hannover
(LUH), Germany*

J. Pascual Vergara and D. Merino

Acciona Energia, Spain

W. Shi and H. Park

*Pohang University of Science and
Technology (POSTECH), Korea*

Abstract

Offshore wind turbines are designed and analyzed using comprehensive simulation codes that account for the coupled dynamics of the wind inflow, aerodynamics, elasticity, and controls of the turbine, along with the incident waves, sea current, hydrodynamics, and foundation dynamics of the support structure. This paper describes the latest findings of the code-to-code verification activities of the Offshore Code Comparison Collaboration, which operates under Subtask 2 of the International Energy Agency Wind Task 23. In the latest phase of the project, participants used an assortment of codes to model the coupled dynamic response of a 5-MW wind turbine installed on a floating spar buoy in 320 m of water. Code predictions were compared from load-case simulations selected to test different model features. The comparisons have resulted in a greater understanding of offshore floating wind turbine dynamics and modeling techniques, and better knowledge of the validity of various approximations. The lessons learned from this exercise have improved the participants' codes, thus improving the standard of offshore wind turbine modeling.

Keywords: offshore wind turbine, floating, spar buoy, aero-hydro-servo-elastic analysis, code verification

1 Introduction

The vast offshore wind resource represents a potential to use wind turbines installed offshore. Design standardization is difficult, however, because offshore sites vary significantly through differences in water depth, soil type, and wind and wave severity. For offshore wind turbine installations to be cost effective, a variety of support structure types is required. These types include fixed-bottom monopiles, gravity bases, and space-frames—such as tripods and lattice frames (“jackets”)—and floating structures. In this context, the offshore wind industry faces many new design challenges.

Wind turbines are designed and analyzed using codes capable of predicting the coupled dynamic loads and responses of the system. Land-based wind turbine analysis relies on the use of aero-servo-elastic codes, which incorporate wind-inflow, aerodynamic (aero), control system (servo), and structural-dynamic (elastic) models in the time domain in a coupled simulation environment. In recent years, some of these codes have been expanded to include the additional dynamics pertinent to offshore installations, including the incident waves, sea current, hydrodynamics, and foundation dynamics of the support structure. The sophistication of these aero-hydro-servo-elastic codes, and

the limited data available with which to validate them, underscore the need to verify their accuracy and correctness. The Offshore Code Comparison Collaboration (OC3), which operates under Subtask 2 of the International Energy Agency (IEA) Wind Task 23, was established to meet this need.

2 Overview of OC3

To test the newly developed codes, the main activities of OC3 are (1) discussing modeling strategies, (2) developing a suite of benchmark models and simulations, (3) running the simulations and processing the simulation results, and (4) comparing and discussing the results. These activities fall under the much broader objectives of

- Assessing the accuracy and reliability of simulations to establish confidence in their predictive capabilities
- Training new analysts how to run and apply the codes correctly
- Investigating the capabilities and limitations of implemented theories
- Refining applied analysis methodologies
- Identifying further research and development needs.

Such verification work, in the past, has led to dramatic improvements in model accuracy as the code-to-code comparisons and lessons learned have helped identify model deficiencies and needed improvements. These results are important because the advancement of the offshore wind industry is closely tied to the development and accuracy of dynamics models.

2.1 Participants and Codes

The OC3 project is performed through technical exchange among a group of international participants who come from universities, research institutions, and industry. In this paper, specifically, results are presented from participants from the National Renewable Energy Laboratory (NREL), Risø National Laboratory of the Technical University of Denmark (Risø-DTU), MARINTEK, the Norwegian University of Science and Technology (NTNU), the Norwegian University of Life Sciences (UMB),

Garrad Hassan & Partners Limited (GH), the Leibniz University of Hannover (LUH), Acciona Energia, and the Pohang University of Science and Technology (POSTECH).

Most of the aero-hydro-servo-elastic codes that have been developed for modeling the dynamic response of offshore wind turbines are tested within OC3. The existing modeling capabilities of the simulation tools used by (and for some, developed by) each participant are summarized in Table 1. In the cases where Table 1 shows the same code being used by multiple OC3 participants, the model development, simulation runs, and data processing were done independently. Further enhancements of the modeling capabilities are planned in the future.

2.2 Project Approach and Phases

The simulation of offshore wind turbines under combined stochastic aerodynamic and hydrodynamic loading is very complex. The benchmarking task, therefore, requires a sophisticated approach that facilitates the identification of sources of modeling discrepancies introduced by differing theories and model implementations in the various codes. This is possible only by (1) meticulously controlling all of the inputs to the codes and (2) carefully applying a stepwise verification procedure where model complexity is increased in each step.

The fundamental set of inputs to the codes controlled within OC3 relates to the specifications of the wind turbine. The OC3 project uses the publicly available specifications of the 5-MW baseline wind turbine developed by NREL, which is a representative utility-scale multi-megawatt turbine. This conventional three-bladed upwind variable-speed variable-blade-pitch-to-feather controlled turbine, is specified with detailed rotor aerodynamic properties; blade, drivetrain, nacelle, and tower structural properties; and generator-torque and blade-pitch control system properties, the latter of which was provided to all OC3 participants in the form of a dynamic link library (DLL). The specifications of the NREL offshore 5-MW baseline wind turbine are available in detail [1]. The hydrodynamic and elastic properties of the varying offshore support structures

FAST	Bladed	ADAMS	HAWC2	3Dfloat	Simo	SESAM / DeepC
Code Developer						
NREL	GH	MSC + NREL + LUH	Risø-DTU	UMB	MARINTEK	DNV
OC3 Participant						
NREL + POSTECH	GH	NREL + LUH	Risø-DTU	UMB	MARINTEK	Acciona + NTNU
Aerodynamics						
(BEM or GDW) + DS	(BEM or GDW) + DS	(BEM or GDW) + DS	(BEM or GDW) + DS	(BEM or GDW)	BEM	None
Hydrodynamics						
Airy ⁺ + ME, Airy + PF + ME	(Airy ⁺ or Stream) + ME	Airy ⁺ + ME, Airy + PF + ME	Airy + ME	Airy + ME	Airy + PF + ME	Airy ⁺ + ME, Airy + PF + ME
Control System (Servo)						
DLL, UD, SM	DLL	DLL, UD	DLL, UD, SM	UD	DLL	None
Structural Dynamics (Elastic)						
Turbine: FEM ^p + (Modal / MBS), Mooring: QSCE	Turbine: FEM ^p + (Modal / MBS), Mooring: UDFD	Turbine: MBS, Mooring: QSCE, UDFD	Turbine: MBS / FEM, Mooring: UDFD	Turbine: FEM, Mooring: FEM, UDFD	Turbine: MBS, Mooring: QSCE, MBS	Turbine: MBS, Mooring: QSCE, FEM
Airy ⁺ – Airy wave theory +) with free surface corrections BEM – blade-element / momentum DLL – external dynamic link library DNV – Det Norsk Veritas DS – dynamic stall		GDW – generalized dynamic wake FEM ^p – finite-element method P) for mode preprocessing only MBS – multibody-dynamics formulation ME – Morison's equation MSC – MSC Software Corporation		PF – linear potential flow with radiation & diffraction QSCE – quasi-static catenary equations SM – interface to Simulink [®] with MATLAB [®] UD – implementation through user-defined subroutine available UDFD – implementation through user-defined force-displacement relationships		

Table 1: Overview of aero-hydro-servo-elastic modeling capabilities

used in the project are also controlled. Furthermore, the turbulent full-field wind inflow and regular and irregular wave kinematics datasets were provided to all participants. This approach eliminates any possible differences brought about by dissimilar turbulence models, wave theories, or stochastic realizations.

An important part of the comparison is a stepwise process that allows the origin of differences between code predictions to be discovered. Various combinations of wave and wind input were introduced with the rotor and tower being rigid or flexible, disentangling the contributions from wind and wave applied loads and dynamic response. Finally, the turbine was made operational so that the effect of the control system could be evaluated.

The emphasis of OC3 is to verify the support structure dynamics as part of the dynamics of the complete system. This emphasis distinguishes OC3 from previous wind turbine code-to-code verification exercises. To encompass the variety of support structures required for cost effectiveness at varying offshore sites, different support structures (for the same wind turbine) are investigated in separate phases of OC3:

- In Phase I, the NREL offshore 5-MW wind turbine is installed on a monopile with a rigid foundation in 20 m of water.
- In Phase II, the foundation of the monopile from Phase I is made flexible by applying different models to represent the soil-pile interactions.
- In Phase III, the water depth is changed to 45 m and the monopile is swapped with a tripod substructure.
- In Phase IV, the wind turbine is installed on a floating spar buoy in deep water (320 m).

The OC3 project started in fall of 2004 and ended in the winter of 2009. A follow up project to OC3 is being initiated in 2010 through the IEA so that two more phases can be considered, including the analysis of a fixed-bottom jacket and a floating semi-submersible. A description of Phases I, II, and III and their results are presented in detail in [2], [3], and [4], respectively. This paper describes Phase IV and discusses its results.

3 Overview of Phase IV

Numerous floating platform concepts are possible for offshore wind turbines, including spar-buoys, tension leg platforms (TLPs),

barges, and hybrid concepts. In OC3 Phase IV, the spar-buoy concept called “Hywind,” developed by Statoil of Norway, was imitated. This concept was chosen for its simplicity in design, suitability to modeling, and the existence of a full-scale prototype. Statoil graciously supplied detailed platform and mooring system data for the conceptual version of the Hywind platform that was developed to support a 5-MW wind turbine, as analyzed in [5, 6]. Per the request of Statoil, the original data was condensed and sanitized to make it suitable for public dissemination. Aspects of the original data were also adapted slightly so that the platform design appropriately supports the NREL 5-MW baseline turbine, which has slightly different properties than the turbine Statoil used to develop their system. The rotor-nacelle assembly of the NREL 5-MW turbine—including the aerodynamic and structural properties—remains the same as in Ref. [1], but the support structure (tower and substructure) and control system properties have been changed. The new system is referred to as the “OC3-Hywind” system, to distinguish it from Statoil’s original Hywind concept. The OC3-Hywind system features a deeply drafted, slender spar buoy with

catenary mooring lines [7].

Floating offshore wind turbines are a good test for aero-hydro-servo-elastic codes because they incorporate a number of features not present in conventional fixed-bottom offshore support structures:

- The introduction of very low frequency modes that can impact the aerodynamic damping and stability of the system;
- The possibility of significant translational and rotational motions of the support structure, which can couple with the motions of the rotor-nacelle assembly;
- The mooring system and anchoring is a new component that must be considered in the overall analysis; and
- The support structure need not be slender and cylindrical (although this is nearly the case in the OC3-Hywind system), such that hydrodynamic radiation, diffraction and other wave effects can become important.

In Phase IV, a set of load-case simulations has been specified for the OC3-Hywind system, as summarized in Table 2. Most of the load cases in Table 2 correspond to those of equivalent simulations from earlier phases (see Refs. [2, 3, 4]). In Phase IV, though, it

Load Case	Enabled DOFs	Wind Conditions	Wave Conditions	Analysis Type
1.2	Platform, tower, drivetrain, blades	None: air density = 0	Still water	Eigenanalysis
1.3	Platform, tower, drivetrain, blades	None: air density = 0	Still water	Static equilibrium solution
1.4	Platform	None: air density = 0	Still Water	Free-decay test time series
4.1	Platform, tower	None: air density = 0	Regular Airy: $H = 6$ m, $T = 10$ s	Periodic time-series solution
4.2	Platform, tower	None: air density = 0	Irregular Airy: $H_s = 6$ m, $T_p = 10$ s, JONSWAP wave spectrum	Time-series statistics, DELs, power spectra
5.1	Platform, tower, drivetrain, blades	Steady, uniform, no shear: $V_{hub} = 8$ m/s	Regular Airy: $H = 6$ m, $T = 10$ s	Periodic time-series solution
5.2	Platform, tower, drivetrain, blades	Turbulent: $V_{hub} = V_r$ (11.4 m/s), $\sigma_1 = 1.981$ m/s, Mann model	Irregular Airy: $H_s = 6$ m, $T_p = 10$ s, JONSWAP wave spectrum	Time-series statistics, DELs, power spectra
5.3	Platform, tower, drivetrain, blades	Turbulent: $V_{hub} = 18$ m/s, $\sigma_1 = 2.674$ m/s, Mann model	Irregular Airy: $H_s = 6$ m, $T_p = 10$ s, JONSWAP wave spectrum	Time-series statistics, DELs, power spectra
5.4	Platform, tower, drivetrain, blades	Steady, uniform, no shear: $V_{hub} = 8$ m/s	Regular Airy: $H = 2$ m, $\omega = 0.1, 0.2, \dots, 3.5$ rad/s	Time-series-generated “effective RAOs”
DEL	– damage equivalent load			
DOF	– degree of freedom			
H	– individual wave height			
H _s	– significant wave height			
		T	– individual wave period	V_r
		T_p	– peak spectral period	σ_1
		V_{hub}	– hub-height wind speed averaged over 10 minutes	– longitudinal wind speed standard deviation
				ω
				– individual wave frequency

Table 2: Summary specifications for the Phase IV load-case simulations

was not necessary to run all of the earlier simulations, and as a result, the load-case identifiers are not sequential.

The load cases new to Phase IV are cases 1.3, 1.4, and 5.4. Case 1.3 is used to compare the static equilibrium condition of the full system void of wind or wave excitation. This case is useful for checking that the combined weight of the rotor-nacelle assembly, tower, and platform balances with the static buoyancy (i.e., weight of the displaced fluid) and mooring reactions identically between the models. Case 1.4 is used to test the OC3-Hywind system's hydrodynamic damping through free-decay tests. This case considers only the six rigid-body DOFs of the platform in still water; each DOF is perturbed separately, and the time-series responses are compared. Case 5.4 is used to test the OC3-Hywind's frequency response. This case considers steady uniform winds without shear at 8 m/s, regular Airy 2-m high waves with different frequencies in each simulation, the turbine control system and all DOFs enabled, and simulates until a periodic steady-state condition is reached. The outputs of case 5.4 are the time-series-generated Response Amplitude Operators ("effective RAOs"). An "effective RAO" is defined here to mean the difference in response amplitudes between nonlinear time-domain simulations run with and without wave excitation. That is, the outputs are the effective amplitudes of the platform motions, turbine displacements, loads, etc. normalized by the wave amplitude (1 m) versus wave frequency. The word "effective" is used to distinguish these values from RAOs that are typically found using linear frequency-domain techniques.

For each load-case simulation, a total of 57 model outputs were analyzed. In addition to the 39 outputs analyzed in Phases I through III for the rotor, drivetrain, nacelle, tower, and environment (again, see Refs. [2, 3, 4]), 18 outputs were used in Phase IV to analyze the loads and deflections of the floating platform and mooring system.

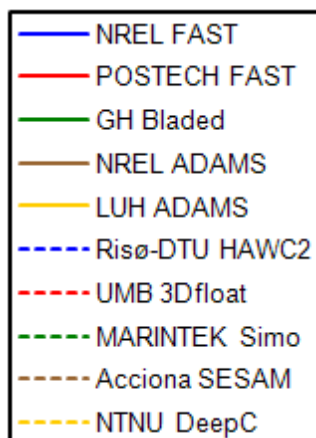


Figure 1: Results Legend

4 Phase IV Results

Each load-case simulation of Phase IV was run by the OC3 participants. The legend in Figure 1 delineates how the results are presented in the figures that follow. The color shade and line type distinguish the results from separate participants and codes. Some results were not processed by all of the OC3 participants, which is why some of the predictions are left blank or have a zero value. Only a small subset of the results is presented.

4.1 Full-System Eigenanalysis

Figure 2 gives the lowest 19 natural frequencies calculated for the stationary OC3-Hywind system in still water from load case 1.2. Results were obtained from all codes except FAST by POSTECH and Bladed. While case 1.2 calls for enabling all system DOFs, the rotor-nacelle assembly is modeled rigidly in ADAMS by LUH and 3Dfloat, and the rotor-nacelle assembly and tower are modeled rigidly in Simo, SESAM, and DeepC. The designation of "pitch" and "yaw" in the asymmetric flapwise and edgewise blade modes identifies coupling of the blade motions with the nacelle-pitching and nacelle-yawing motions, respectively.

Most of the codes agree on their predictions of the lowest six natural frequencies, which correspond to the six (primarily) rigid-body modes of the floating support platform (with only minor couplings to the turbine flexibilities). The platform roll and pitch natural frequencies are predicted higher by

Risø-DTU with the HAWC2 code. While these differences are still being investigated, one thought is that they are caused by the treatment of gravity in the model linearization process, as gravity has a strong influence on the roll and pitch restoring of a deep-drafted spar.

Not all of the codes predict the natural frequencies of the flexible body modes. The codes that model the tower and blade bending and drivetrain torsion modes predict similar natural

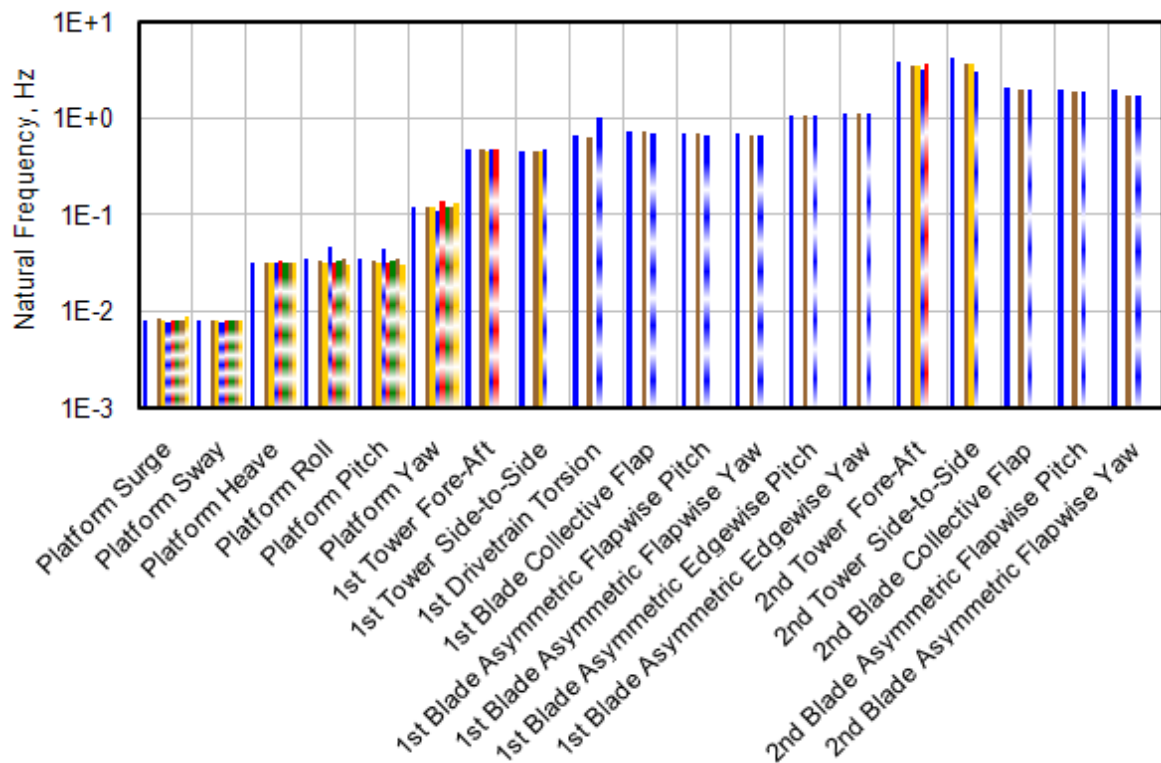


Figure 2: Full-system hydro-elastic natural frequencies from load case 1.2

frequencies, with only slight discrepancies. The discrepancy in the second blade asymmetric flapwise yaw frequency has been seen in earlier phases of OC3, particularly Phase II [3]. In this mode, the vertically positioned blade remains stationary, while the two other blades flap out of phase with each other. These blade motions couple with the torsion of the tower and—in Phase IV—the yaw of the platform (both being rotations about the tower centerline). The codes which do not account for tower torsion (FAST) predict higher natural frequencies—corresponding to the stiffer compliance about the tower centerline—than the codes that do (ADAMS, HAWC2).

4.2 Free Decay

Figure 3 and Figure 4 give the platform surge and pitch time series from perturbations in platform surge and pitch, respectively, from the free-decay tests of load case 1.4. Results were obtained from all codes except Bladed and DeepC.

For the surge free-decay test of Figure 3, all codes except FAST by POSTECH agree on

the surge displacement. Both NREL and POSTECH used FAST and their results compare well, except that there is less hydrodynamic damping in POSTECH's results. This is caused by POSTECH's FAST model missing one hydrodynamic damping term (the so-called “additional linear damping” specified for the OC3-Hywind spar). The pitch-surge coupling can be placed into two groups—FAST by POSTECH and ADAMS by LUH in one, and FAST and ADAMS by NREL, HAWC2, 3Dfloat, and SESAM in another. The pitch offset results from the overhanging mass of the rotor-nacelle assembly from the centerline of the tower and platform.

All codes agree on the platform-pitch response in the pitch free-decay test of Figure 4, except ADAMS by LUH, which predicts too little damping. HAWC2 predicts different surge-pitch couplings than the other codes.

4.3 Hydro-Elastic Response with Regular Waves

Figure 5 shows time histories of platform surge, heave, and pitch displacements; tower-top fore-aft deflection and shear force; and downstream fairlead tension (from mooring line #1) from load case 4.1. This case considers the response of the platform and flexible tower (with rigid rotor-nacelle-assembly) excited by regular (i.e., periodic) waves. Results were obtained from NREL with FAST and ADAMS, Risø-DTU with HAWC2, UMB with 3Dfloat, MARINTEK with Simo, and Acciona with SESAM. The responses for two wave passages (i.e., periods) are shown. All codes removed start-up transients from their results. The instantaneous wave elevation at the platform centerline is highest at 0 and 10 s and lowest at 5 and 15 s, except in 3Dfloat and Simo, which are phase-shifted relative to the other codes.

In these results, all codes agree on the

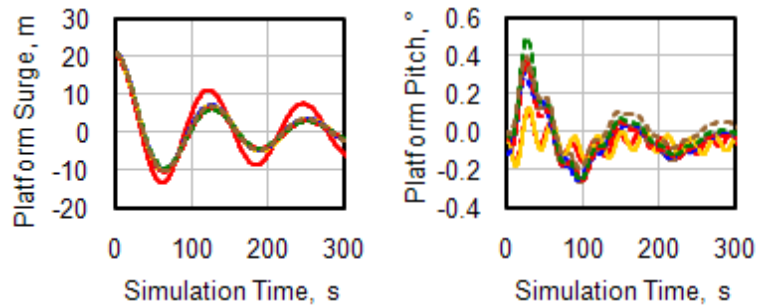


Figure 3: Free decay in platform surge from load case 1.4

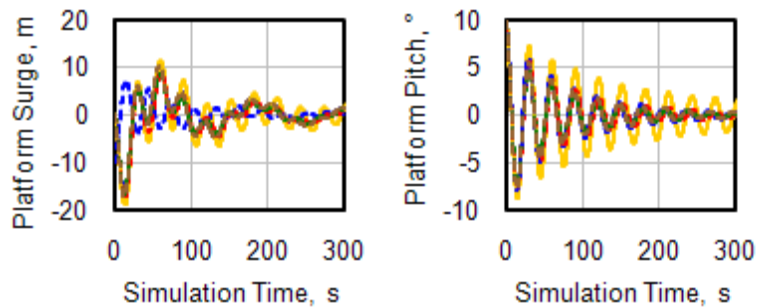


Figure 4: Free decay in platform pitch from load case 1.4

platform-surge amplitude except HAWC2, which may simply have output the wrong parameter. For pitch and heave, all codes agree. For tower fore-aft deflection—deflection induced by platform motion—most codes agree quite well. Simo and SESAM predict no deflection because the tower was

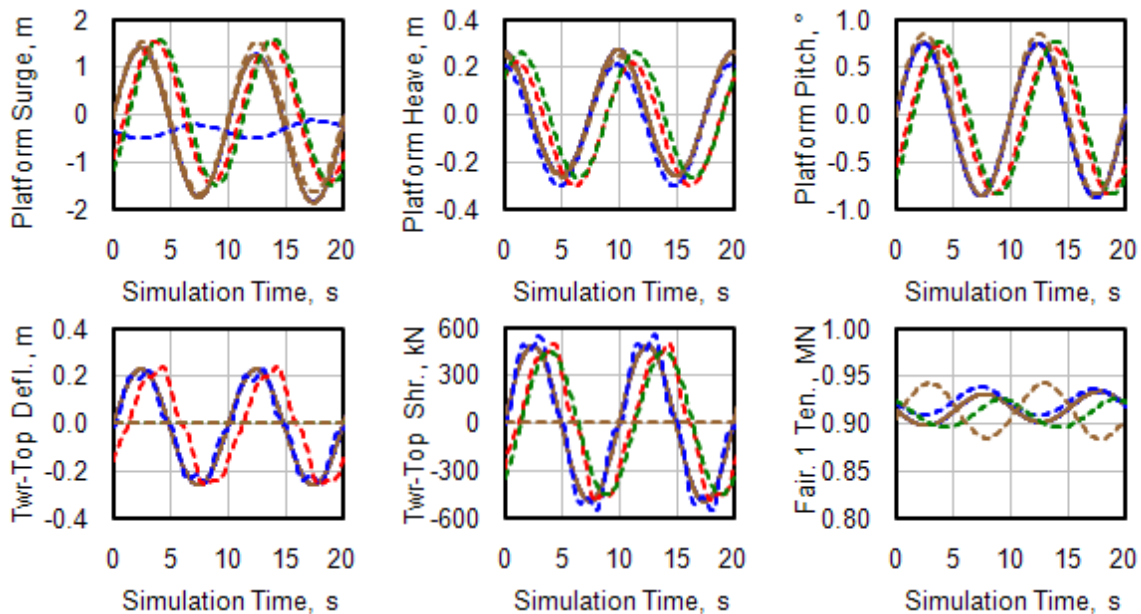


Figure 5: Hydro-elastic time series with regular waves from load case 4.1

modeled rigidly in those codes. The tower-top fore-aft shear force (induced by the oscillating mass of the rotor-nacelle assembly) and downstream fairlead tension agree well in all codes except SESAM.

4.4 Hydro-Elastic Response with Irregular Waves

Figure 6 shows power spectra computed in load case 4.2 for the same parameters shown in Figure 5. Case 4.2 tests the same model used in case 4.1, but with excitation from irregular (stochastic) waves. Results were obtained from all codes except FAST by POSTECH, ADAMS by LUH, and 3Dfloat. Because several codes contain start-up transients, the statistical results from this case are difficult to compare and are not presented.

The wave spectrum has the highest amount of energy at 0.1 Hz, corresponding to the peak-spectral period of 10 s. All codes agree on the energy content of the system responses at this frequency, except SESAM in platform pitch. The platform natural frequencies (about 0.008 Hz in surge, 0.032

Hz in heave, and 0.034 Hz in pitch) are easily visible in the platform-displacement power spectra of all codes; however, the codes differ on their predictions of energy content at and around these frequencies (with the farthest outliers being Bladed in surge, Simo in heave, and SESAM in pitch). Spectral shape estimates in this frequency range are sensitive to time-series sampling. There is considerable statistical uncertainty of response spectra because of the relatively short duration of the prescribed time series compared to the wave and platform periods.

In the tower-top fore-aft deflection and shear force power spectra, the platform-pitch and first tower bending (about 0.46 Hz) natural frequencies are clearly visible. Bladed, however, shows more energy just below the first tower bending natural frequency and less energy at the platform-pitch natural frequency. SESAM and DeepC predict higher energy than the other codes in fairlead tension above 0.1 Hz, likely the result of undamped high-frequency motions in their FEM-based mooring line solution.

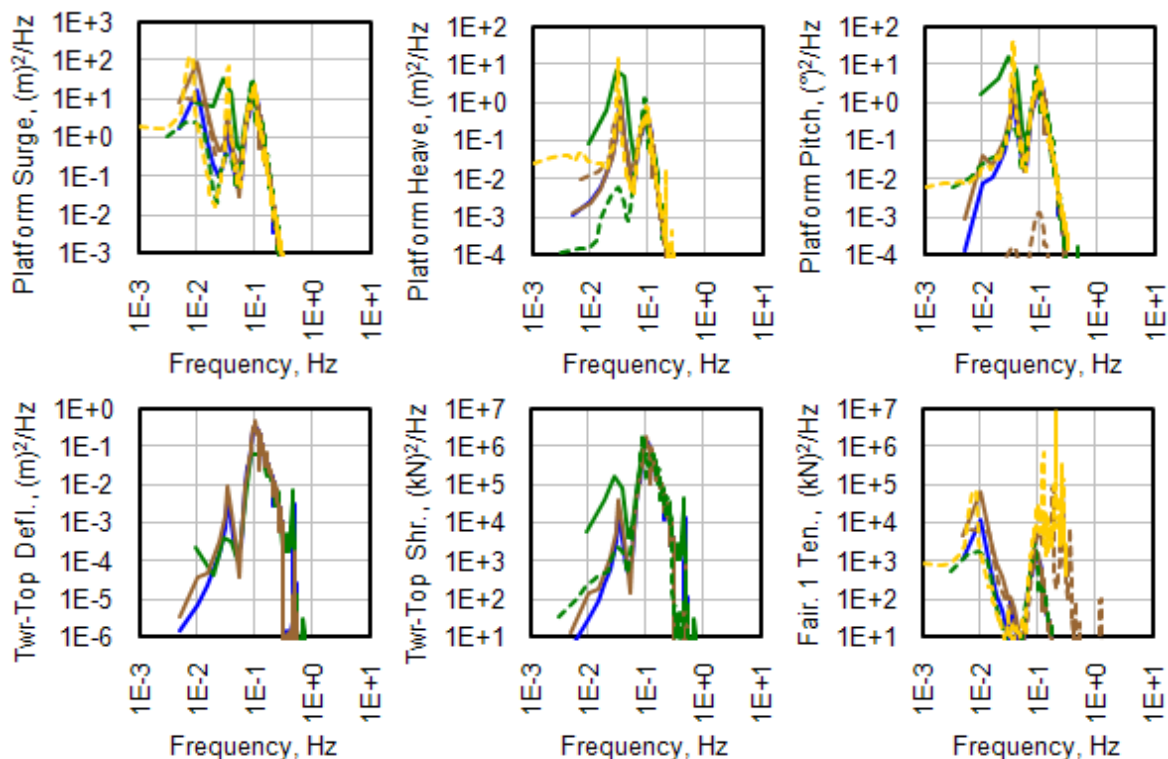


Figure 6: Hydro-elastic power spectra with irregular waves from load case 4.2

4.5 Aero-Hydro-Servo-Elastic Response with Regular Waves

Figure 7 gives time histories of out-of-plane blade-tip deflection; generator power; rotor speed; platform surge, heave, pitch, and yaw displacements; tower-top fore-aft deflection, shear force, and rotor torque; and downstream and upstream fairlead tensions (from mooring line #1 and #2) from load case 5.1. This case is like 4.1 except that the rotor

and drivetrain are flexible, the controller is enabled, and the turbine is operating in uniform wind below rated wind speed. In addition to the wind excitation, which leads to nonzero mean loads and displacements, the system is again excited by regular waves that induce oscillations about the means. The responses are shown for two wave passages (i.e., periods)—which equates to about three rotor revolutions—after all start-up transients have died out. Results were obtained from all

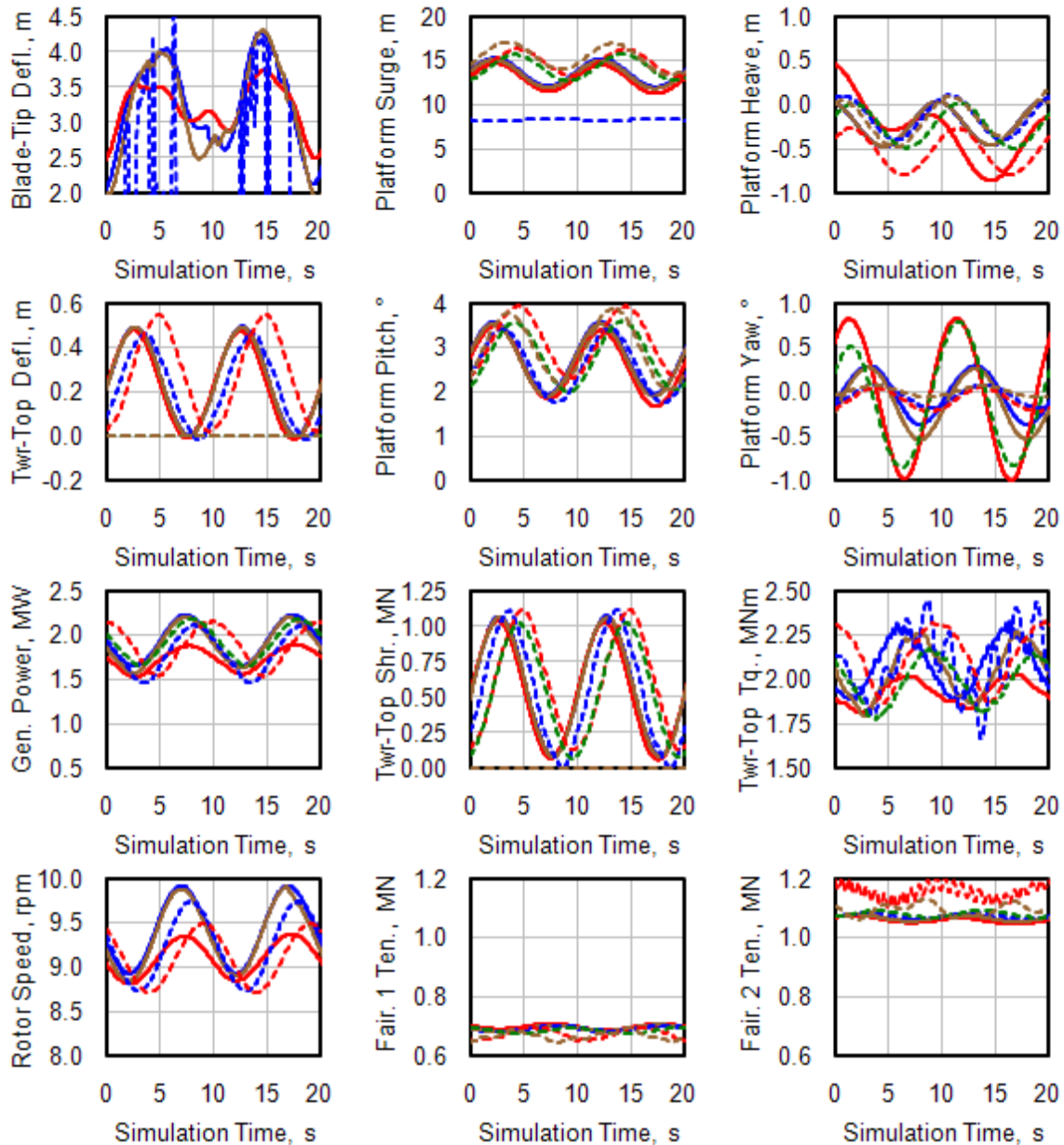


Figure 7: Aero-hydro-servo-elastic time series with regular waves from load case 5.1

codes but Bladed, ADAMS by LUH, and DeepC. The instantaneous wave elevation at the platform centerline is highest at 0 and 10 s and lowest at 5 and 15 s, except in 3Dfloat and Simo, which are phase-shifted relative to the other codes.

The generator power agrees quite well between all codes (at least as well as they have in earlier OC3 phases), except FAST by POSTECH, which predicts a lower mean and amplitude. Likewise, all codes agree well in rotor speed, except FAST by POSTECH and 3Dfloat, which predict lower means and amplitudes.

The out-of-plane blade-tip deflection agrees reasonably well between all codes except FAST by POSTECH, which has less overall oscillation, and HAWC2, which may simply have output the wrong parameter. 3Dfloat, Simo, and SESAM predict no deflection because their rotors were modeled rigidly.

Except for FAST by POSTECH, all codes predict a similar mean value of the tower-top rotor torque (i.e., roll moment), but the oscillations about this mean vary. FAST by POSTECH predicts a lower mean and oscillation amplitude. All codes agree on the tower-top fore-aft shear (thrust) force, but 3Dfloat results in a larger tower-top deflection. Simo and SESAM predict no deflection because the tower was modeled rigidly in those codes.

For the platform-surge displacement, all codes but HAWC2 agree on the amplitude of oscillation, but the mean values vary despite the agreement on thrust—Simo, 3Dfloat, and SESAM are a bit higher and HAWC2 is very low (HAWC2 also has less amplitude). The results are similar for platform-pitch displacement, except that HAWC2 matches the majority of codes much better. The nonzero means in these displacements are the result of the nonzero mean rotor thrust. The higher amount of platform-surge and -pitch displacements in 3Dfloat results from the slightly higher mean thrust.

The rotor thrust is counteracted by tensions in the mooring lines, with the downstream mooring line less loaded than the upstream lines. The variations in the fairlead tensions are fairly consistent with the variations in

platform displacement. That is, the downstream fairlead has a lower tension and the upstream fairleads have higher tension in 3Dfloat and SESAM than in the other codes.

The differing platform-heave displacements imply that the codes differ in how they couple heave with surge and pitch. The slightly negative mean platform-yaw displacement—predicted similarly by most codes—results from the rotor-shaft tilt, which causes some of the rotor torque to act about the yaw axis. The oscillation about this mean—resulting from a gyroscopic moment produced by platform pitching (at the wave period) in combination with spinning rotor inertia—varies a bit between the codes.

4.6 Aero-Hydro-Servo-Elastic Response with Irregular Waves

Figure 8 shows power spectra computed in load case 5.3 for the same parameters shown in Figure 7. Case 5.3 tests the same model used in case 5.1, but with excitation from stochastic wind above rated wind speed and irregular (stochastic) waves. Results were obtained from NREL and POSTECH with FAST, GH with Bladed, NREL with ADAMS, MARINTEK with Simo, and Acciona with SESAM.

The power spectra agree very well in most parameters. As in case 4.2, the wave spectrum has the highest amount of energy at 0.1 Hz—corresponding to the peak-spectral period of 10 s—and all codes agree on the energy content of the system response at this frequency, except SESAM in platform-pitch displacement. Unlike case 4.2, there is a high amount of energy at low frequencies (below 0.1 Hz)—corresponding to the highest energy in the wind—and all codes agree on the energy content of the system response at these frequencies, except SESAM again in platform-pitch displacement and Simo in generator power. Simo also has more energy in the generator power above 0.1 Hz. As in the previous SESAM results, the higher energy content in the fairlead tensions above 0.1 Hz is clearly visible. The second tower and blade bending natural frequencies are visible in the FAST, Bladed, and ADAMS predictions of the tower-top shear force and

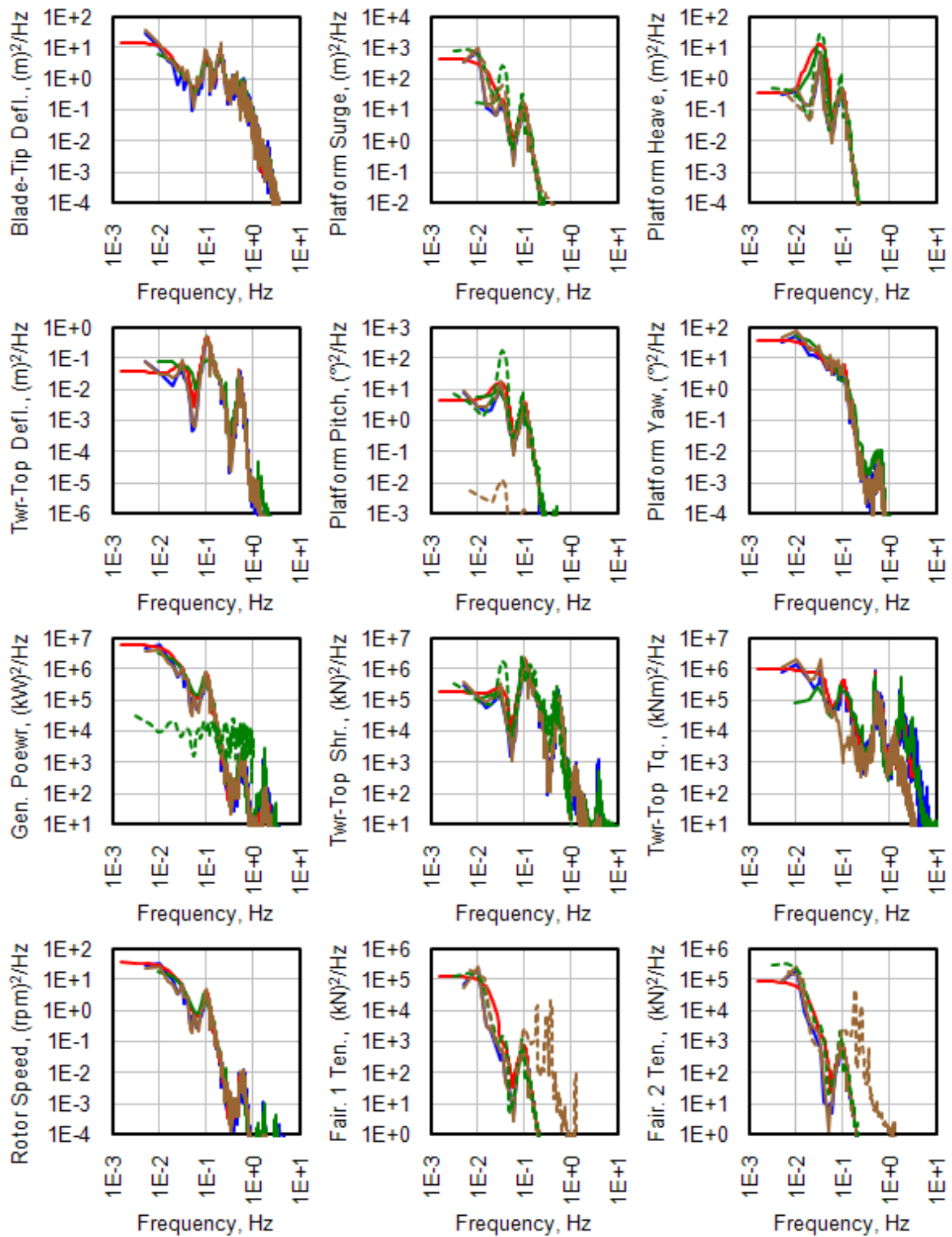


Figure 8: Aero-hydro-servo-elastic power spectra with irregular waves from load case 5.3

rotor torque. However, ADAMS predicts less energy at these frequencies, which may result from the increase in numerical damping with frequency that is typical of ADAMS simulations.

5 Conclusions

The OC3 project has performed work to verify the accuracy and correctness of comprehensive simulation codes that model offshore wind turbine systems' coupled dynamic aero-hydro-servo-elastic response.

In Phase IV of OC3, participants used an assortment of codes to model the coupled dynamic response of the NREL 5-MW wind turbine installed on the OC3-Hywind spar buoy. Code predictions were compared from load-case simulations selected to test different model features. The comparisons have resulted in a greater understanding of offshore floating wind turbine dynamics and modeling techniques, and better knowledge of the validity of various approximations.

The verification activities performed in OC3 are important because the advancement of the offshore wind industry is closely tied to the development and accuracy of dynamic models. Not only have vital experiences and knowledge been exchanged among the project participants, but the lessons learned have helped identify deficiencies in existing codes and needed improvements, which will be used to improve the accuracy of future predictions.

References

- [1].Jonkman J, Butterfield S, Musial W, and Scott G. *Definition of a 5-MW Reference Wind Turbine for Offshore System Development*. NREL/TP-500-38060. NREL: Golden, CO, 2009.
- [2].Passon P, Kühn M, Butterfield S, Jonkman J, Camp T, and Larsen TJ. "OC3—Benchmark Exercise of Aero-Elastic Offshore Wind Turbine Codes." *The Second Conference on The Science of Making Torque From Wind*, 28–31 August, Copenhagen, 2007.
- [3].Jonkman J, et al. "Offshore Code Comparison Collaboration within IEA Wind

Annex XXIII: Phase II Results Regarding Monopile Foundation Modeling." *2007 European Offshore Wind Conference & Exhibition*, 4–6 December, Berlin, 2007.

- [4].Nichols J, et al. "Offshore Code Comparison Collaboration within IEA Wind Annex XXIII: Phase III Results Regarding Tripod Support Structure Modeling." *47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exhibition*, 5–8 January, Orlando, FL, 2008. (DVD-ROM)
- [5].Nielsen FG, Hanson TD, and Skaare B. "Integrated Dynamic Analysis of Floating Offshore Wind Turbines." *25th International Conference on Offshore Mechanics and Arctic Engineering*, 4–9 June, Hamburg, 2006. (CD-ROM)
- [6].Skaare B, Hanson TD, and Nielsen FG. "Importance of Control Strategies on Fatigue Life of Floating Wind Turbines." *26th International Conference on Offshore Mechanics and Arctic Engineering*, 10–15 June, San Diego, CA, 2007. (CD-ROM)
- [7].Jonkman J. *Definition of the Floating System for Phase IV of OC3*. NREL: Golden, CO, 2009 (to be published).